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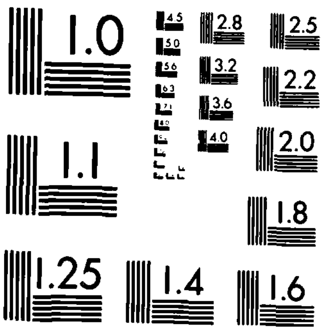
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RADC-TR-85-60
Interim Report
March 1985

SCATTERING FROM FOLIAGE COVERED TERRAIN

Applied Science Associates, Inc.

Gary S. Brown

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, NY 13441-5700

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A brief review of efforts directed toward modeling the effects of foliage covered rough terrain on electromagnetic scattering is presented. A "two-way passage" approach is proposed as an approximate method of solution. In this approach, an incident field is transmitted through a foliage layer in free space. The field transmitted through the foliage acts as an incident field upon the rough surface. The field scattered by the surface is taken to be a secondary incident field upon the foliage slab. The net scattered field is the sum of surface scattered field and the two fields scattered from the foliage. Although the Foldy-Twersky theory can be used to account for the propagation through the foliage, investigations of the method of smoothing are also being carried out. The method of smoothing is also proposed for use in the surface scattering part of the problem. Particular attention is directed toward the asymptotic evaluation of the first interaction terms in this formalism.

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1.0 INTRODUCTION AND SUMMARY

One of the most difficult problems facing electromagnetics is the analysis of the effects of natural terrain on radiated fields. While some progress has definitely been made on developing a good theory for scattering from surfaces having a well defined continuous profile, such surfaces are not, in general, representative of natural terrain. This is because most natural terrain has some form of cover superimposed on the continuous profile. This cover is usually some form of vegetation, snow, ice, or even rubble such as gravel or dead vegetation. This cover represents a significant difficulty to the analyst because it places yet another scattering medium upon one which is complex by itself. Fortunately, the physical nature of some types of cover such as vegetation render it amenable to a statistical characterization. Thus, to analyze the effects of the foliage on electromagnetic fields, we must be able to describe the scattering characteristics of a discretely random media (foliage) superimposed upon a continuously varying random boundary (the underlying surface). This is the problem which we are attempting to resolve, and this report is a brief summary of essentially one year's work.

In Chapter 2 we discuss the relevant parameters of typical foliage coverings and use these results to develop a rationale for the problem. Our approach essentially includes a first order interaction between the foliage and the rough surface and we indicate how the results can be used to determine when our first order interaction approximation becomes inadequate. In order to account properly for the interaction between the foliage and the surface we need an approach to analyze the scattering from the foliage which is potentially capable of yielding more than just the first two moments of the scattered field. For this reason we choose to use the method of smoothing but in a manner which has (to the author's knowledge) never been tried before. We discuss the problems we have initially encountered with this approach and their relationship to previous analytical efforts. We then note that our future efforts will be directed toward developing suitable approximations but with the caveat that we understand the implications of the simplifications particularly in regard to the inclusion of multiple scattering.

In Chapter 3 we discuss our continuing efforts to develop a tractable theory for scattering from the rough surface which includes multiple scattering. In particular, we concentrate our attention on the previous results we obtained with the method of smoothing. We show that although the integrations resulting from the application of this method are very difficult to perform in general, they do appear to simplify considerably in certain asymptotic limits. Furthermore, we illustrate how these asymptotics can be used to simplify the integrations. We also discuss our efforts to understand the convergence of the method of smoothing as it applies to the rough surface scattering problem. Unfortunately, we have been unable to determine the range of surface parameters for which the method converges. However, we do show that even the first order smoothing approximation does sum an infinite number of interactions on the surface under certain simplifying conditions. Future work on this problem will be directed toward numerical evaluations of the asymptotic approximations for the above noted integrations.

2.0 FOLIAGE COVERAGE ANALYSIS

2.1 Background

The primary thrust of this research effort is to provide a tractable theory for estimating the effects of a vegetation cover upon scattering from arbitrarily roughened terrain. Since the eventual goal of our work is to aid in the estimation and elimination of both incoherent and coherent clutter in radar systems, our theory must be sufficiently general to account for various types of vegetation cover ranging from rather short grass to dense, cultivated forests. Needless to say, this is a very difficult problem not only from the electromagnetic analysis point of view but also from the perspective of how one translates the rather crude biophysical characterizations of foliage[@] into meaningful scattering parameters. About the only thing we have in our favor is that the fractional volume occupied by foliage is generally less than 1% with the exceptions being no more than 5% for well maintained forested areas in eastern Europe [Brown & Curry, 1980]. The primary implication of this fact is that we can use a weak multiple scattering theory for the average or coherent field in the foliage [Brown & Curry, 1980]. This simplification greatly reduces the complexity of the foliage-only problem from the electromagnetic point of view and has, in fact, formed the basis of all approximate theories to date.

Fung [1982] has recently published a recipe oriented review of previous efforts to model the scattering from foliage. Unfortunately, Fung failed to emphasize a very important fundamental dichotomy in these approximate theories; the great majority of these approximate theories are derived from continuous random media theory while only a relatively few are based on the truly discrete nature of the random media. The primary difficulty with trying to use continuous random media theory for truly discrete media is that one is forced into defining a number of equivalent continuous characteristics for the discrete media. Since these equivalent continuous characteristics do not physically exist, there is no rigorous way to measure them and, hence, there is no way to verify the theory experimentally. What generally happens is that one ends up with a parameter laden model and the parameters are chosen to fit the

[@]The problem is further compounded by the fact that even this crude biophysical data is seldom available.

model to selected scattering data. Unfortunately, this approach provides us with neither confidence in nor guidance as to how the model can be extrapolated to other frequencies, polarizations, environments, etc. Of course, if one had a very large data base available to corroborate the model then it certainly could be used; however, if such a large data base is available, then why not simply develop an empirical model in the first place? In summary, we do not plan to use nor do we intend to develop any theories based on wave propagation and scattering in equivalent continuous random media. Our principal reason for this decision is that in such an approach we lose the ability to correlate the physical properties of the foliage with the actual parameters required by the model or theory. We feel very strongly that such a capability is vitally important to understanding a problem of this complexity.

Lang [1981] and Lang & Sidhu [1983] have recently done an excellent job of estimating the scattering properties of an infinite half-space of foliage and a layer of foliage on a planar ground, respectively, using discrete rancom media theory. For the half-space problem, Lang [1981] uses the Foldy-Twersky formalism to determine the wavenumber for the average or coherent field and the distorted Born approximation to find the incoherent scattered power. As he uses it, the distorted Born approximation assumes that the individual particles scatter independently of each other but in an effective background medium whose characteristics are determined by the propagation characteristics of the coherent field. Although the distorted Born approximation is a single scatter based theory, it does account for the attenuation of the coherent field before and after it strikes a particle. The same basic concepts are applied to the foliage slab on a planar ground problem although the analysis is somewhat more involved because of the presence of three media. In particular Lang & Sidhu [1983] treat the propagation of the mean field via a one dimensional differential equation which they solve approximately via a two variable perturbation technique based upon the small fractional volume of the foliage. This approach allows them to clearly identify the various scattering mechanisms which are important when the fractional volume is small. This is a very powerful approach and leads to a great deal of insight into the problem. Unfortunately, it is not obvious how this rigorous approach could be applied to a situation where the ground surface is randomly roughened. However, Lang's work does provide us with an excellent check case when the variance of the surface roughness shrinks to zero.

2.2 Approach

There are a number of *a priori* approximate techniques that could be considered as potential candidates for analyzing the effects of a foliage layer on a randomly rough surface. For example, we could simply add the scattering cross sections of the foliage layer and the rough surface. Clearly, this result will be valid only when one of the cross sections is significantly larger than the other. We might also consider adding the cross section of the foliage to a reduced cross section for the ground; the reduction factor could be interpreted as somehow accounting for the attenuating effects of the foliage upon the field that actually reaches the ground. The fundamental difficulties with *a priori* approaches of this type are that (a) they ignore the interaction of coherent and incoherent fields and (b) they provide absolutely no indication as to when they become inaccurate. For these reasons, we have selected a more direct approximate approach to the problem which we feel will be suitable for a foliage covering in that it is both tractable and has the potential for indicating when it begins to fail.

The dominant effects of the foliage upon the scattering by the rough surface are twofold; first, the foliage alters the field incident upon the surface and, second, it changes the field scattered by the rough surface. Similarly, the surface gives rise to a secondary field incident upon the foliage from below. This simple reasoning suggests that we can approximately account for the foliage by using only the suspected dominant interactions between the surface and the foliage. That is, we first consider a layer of foliage <u>in free space</u> which is illuminated by the source or incident field $\vec{E}_i$. The foliage gives rise to a scattered field which we denote by $\vec{E}_{s_f}^{(1)}$; thus, the <u>total field</u> below the foliage layer is $\vec{E}_i + \vec{E}_{s_f}^{(1)}$. We take this field to be the field incident upon the rough surface which, in turn, produces a scattered field $\vec{E}_{s_s}^{(1)}$ above the surface. This field now acts as an incident field on the foliage layer which, subsequently, gives rise to a scattered field $\vec{E}_{s_f}^{(2)}$ above the foliage layer. Clearly, we could continue this process indefinitely to find that the net scattered field due to the foliage covered rough surface is given by

$$\vec{E}_s = \sum_{j=1}^{\infty} \vec{E}_{s_f}^{(j)} + \sum_{j=1}^{\infty} \vec{E}_{s_s}^{(j)} \tag{2.1}$$

However, truncating the series in (2.1) to the terms we expect to be dominant in the process, we obtain

$$\vec{E}_s \approx \vec{E}_{s_f}^{(1)} + \vec{E}_{s_f}^{(2)} + \vec{E}_{s_s}^{(1)} \tag{2.2}$$

To be more explicit, let us insert in the argument of each field in (2.2) the effective incident field for that particular scattered field, i.e.,

$$\vec{E}_s \approx \vec{E}_{s_f}^{(1)}(\vec{E}_i) + \vec{E}_{s_f}^{(2)}(\vec{E}_{s_s}^{(1)}) + \vec{E}_{s_s}^{(1)}(\vec{E}_i + \vec{E}_{s_f}^{(1)}) \tag{2.3}$$

This expression shows more clearly that (a) the first order field scattered from the foliage $(\vec{E}_{s_f}^{(1)})$ is due to the free space incident field $(\vec{E}_i)$, yield

$$\iint \zeta_{q_1}\zeta_{p_o}\, p\,(\zeta_1,\zeta_o,\zeta_{q_i},\zeta_{p_o})\,d\zeta_{q_1}\,d\zeta_{p_o} = \overline{p}(\zeta_1,\zeta_2)$$

Now, both p and $\overline{p}$ also contain an explicit dependence upon the surface height correlation function $\langle\zeta^2\rangle\rho(\Delta\vec{r}_t)$ and its spatial derivatives. Thus, all of the terms in (3.3) depend only on $\Delta\vec{r}_t = \vec{r}_{t_1}-\vec{r}_{t_2}$, so converting to this difference coordinate yields

$$LPGf^i = \exp(-j\vec{k}_{i_t}\cdot\vec{r}_{t_1}) \iiint \phi(\zeta_1-\zeta_o,\Delta\vec{r}_t)\overline{p}(\zeta_1,\zeta_o;\Delta\vec{r}_t)\exp[j(k-k_{i_z})\zeta_o]$$

$$\cdot\ \exp(j\vec{k}_{i_t}\cdot\Delta\vec{r}_t)\,d\zeta\,d\zeta_o\,d\Delta\vec{r}_t \tag{3.4}$$

It is also convenient to convert to a difference in ζ_1 and ζ_o . That is, we let $\Delta\zeta = \zeta_1 - \zeta_o$ and (3.4) becomes

$$LPGf^i = \exp(-j\vec{k}_{i_t}\cdot\vec{r}_{t_1}) \iiint \phi(\Delta\zeta,\Delta\vec{r}_t)\overline{p}(\Delta\zeta+\zeta_o,\zeta_o;\Delta\vec{r}_t)\exp[j(k-k_{i_z})\zeta_o]$$

$$\cdot\ \exp(j\vec{k}_{i_t}\cdot\Delta\vec{r}_t)\,d\zeta_o\,d\Delta\zeta\,d\Delta\vec{r}_t \tag{3.5}$$

We can now do the ζ_o-integration to yield

$$LPGf^i = \exp(-j\vec{k}_{i_t}\cdot\vec{r}_{t_1}) \iint \phi(\Delta\zeta,\Delta\vec{r}_t)\,\overline{\overline{p}}\,(\Delta\zeta,\Delta k;\Delta\vec{r}_t)\exp(j\vec{k}_{i_t}\cdot\Delta\vec{r}_t)\,d\Delta\zeta\,d\Delta\vec{r}_t \tag{3.6}$$

where $\Delta k = k - k_{i_z}$ and

$$\overline{\overline{p}}(\Delta\zeta,\Delta k;\Delta\vec{r}_t) = \int \overline{p}\,(\Delta\zeta+\zeta_o,\zeta_o;\Delta\vec{r}_t)\,\exp\,[j(k-k_{i_z})\zeta_o]\,d\zeta_o$$

smoothing result which do not include the f^i factor but if we can do the integrations and averages with f^i included then we can certainly do them with f^i absent.

To illustrate the asymptotics, we will consider first the $N=0$ term in detail and then briefly outline the extension to the case where $N>0$. In terms of its functional dependence we can write

$$LPGf^i = \int \langle \phi(\zeta_1-\zeta_o,\vec{r}_{t_1}-\vec{r}_{t_o})\zeta_{q_1}\zeta_{p_o}\exp[j(k-k_{i_z})\zeta_o]\exp(-j\vec{k}_{i_t}\cdot\vec{r}_{t_o})\rangle d\vec{r}_{t_o} \qquad (3.3)$$

where

$$\phi(\zeta_1-\zeta_o,\vec{r}_{t_1}-\vec{r}_{t_o}) = \frac{\partial g(\zeta_1-\zeta_o,\vec{r}_{t_1}-\vec{r}_{t_o})}{\partial \Delta q}$$

$$g(\zeta_1-\zeta_o,\vec{r}_{t_1}-\vec{r}_{t_o}) = \frac{\exp(-jk_o|\vec{r}_{t_1}-\vec{r}_{t_2}+\hat{z}(\zeta_1-\zeta_o)|)}{|\vec{r}_{t_1}-\vec{r}_{t_o}+\hat{z}(\zeta_1-\zeta_o)|}$$

$$\zeta_{q_1} = \frac{\partial\zeta_1}{\partial q_1} \qquad\qquad \zeta_{p_o} = \frac{\partial\zeta_o}{\partial p_o}$$

$$\vec{r}_{t_1} = x_1\hat{x} + y_1\hat{y} \qquad\qquad \vec{r}_{t_o} = x_o\hat{x} + y_o\hat{y}$$

and q_1 and p_o signify either x_1 or y_1 and x_o or y_o, respectively. Also, Δq stands for either $\Delta x = x_1 - x_o$, $\Delta y = y_1 - y_o$, or $\Delta\zeta = \zeta_1 - \zeta_o$. The $\vec{k}_{i_t}$ is the x and y parts of the incident wavenumber vector, k_{i_z} is the z part, and k is arbitrary; for the coherent scattered field we set $k = -k_{i_z}$. The averaging operation in (3.3) requires multiplying the integrand by the joint density function $p(\zeta_1,\zeta_o,\zeta_{q_1},\zeta_{p_o})$ and then integrating over $\zeta_1,\zeta_o,\zeta_{q_1}$, and ζ_{p_o}. The slope integrations can be easily done symbolically we know that an iterative solution will converge in the high frequency limit provided a sufficient number of iterations are taken. We also know that when the surface slopes are moderate to large, the number of required iterations may be large [Ch. 5 of Brown, 1984a]. Since there is no reason to expect that the convergence rate of the transformed integral equation should be different than the convergence rate for the coordinate space equation, we do not feel that iteration is a fruitful approach. Thus, in regard to the integral equations produced by the stochastic Fourier transform approach, we have been unable to develop a suitable asymptotic technique for solving these equations. While we do not plan to abandon our search for some form of asymptotic solution of the integral equations resulting from the stochastic Fourier transform approach, we will not be putting as much effort into this problem as previously. One of the primary reasons for this decision is that the method of smoothing approach appears to be much more amenable to asymptotic solution.

The method of smoothing as it applies to the rough surface scattering problem is developed in detail in Chapter 4 of [Brown, 1984a]. The results of our attempts to apply asymptotic techniques to the method of smoothing are most encouraging but incomplete at this time. Consequently, we shall only broadly outline the rationale of our method of attack and illustrate its merits. The key to evaluating the terms in the method of smoothing solution rests with our ability to evaluate terms like

$$LPG[LG]^N f^i \qquad (N = 0,1,\cdots)$$

where L is an integral over the x and y source coordinates, P is the averaging operator, G comprises products of the gradient of the free space Green's function evaluated on the surface with x and y components of the surface slope, and f^i is the single scattering result (see Ch. 4 of [Brown, 1984a] for a detailed explanation of these terms). There are some terms in the method of

3.2 Asymptotic Approximations

In this section we shall briefly summarize our attempts to apply asymptotic approximations to the rough surface formulations we have previously developed. We have spent a great deal of time attempting to apply asymptotics to simplifying the integral equations we obtained with the stochastic Fourier transform approach, i.e., either the integral equation of the first kind for the transform of the current [Brown, 1981] or the integral equation of the second kind for the average scattered field [Brown, 1984a]. Although we have not been successful in our attempts, we think we know the reason why. The only obvious way to simplify the integral equations we obtained using the stochastic Fourier transform approach was to apply the asymptotics to the kernel of the integral equation. However, when we did this, we did not always obtain self consistent results. The reason for this anomally is that it is not always correct to attribute the asymptotic behavior of an integral equation entirely to the asymptotic behavior of the kernel. That is, the unknown function in the integral equation may also asymptotically approach a limiting form which is just as important as the kernel and ignoring this behavior can lead to erroneous results. While this understanding is clearly worthwhile, the fact remains that we have been unsuccessful in our attempts to asymptotically solve the integral equations resulting from the stochastic Fourier transform approach.

We have also studied solving the integral equation of the second kind for the average scattered field [Ch. 3 of Brown, 1984a] by means of iteration. There is, however, a distinct uncertainty in an iterative approach due to the fact that we seldom know very much about the convergence properties of the iterative solution. In general, it is very difficult to determine the convergence range for a given integral equation. However, from our previous work with the magnetic field integral equation in coordinate space [Ch. 5 of Brown, 1984a], function as follows;

$$G(|\vec{R}-\vec{R}_o|) = \frac{\exp(-jk_o\sqrt{(x-x_o)^2 + (y-y_o)^2 + (z-z_o)^2}}{4\pi\sqrt{(x-x_o)^2 + (y-y_o)^2 + (z-z_o)^2}} \qquad (3.1\ )$$

The average scalar field is obtained by simply averaging (3.1) over all possible realizations of the random variable z_o , i.e.,

$$G(|\vec{R}-\vec{R}_o|) = \int_{-\infty}^{\infty} G(|R-R_o|)\, p\,(z_o)\, dz_o \qquad (3.2)$$

Equation (3.2) clearly shows the fundamental difficulty. That is, because of the form of $G(|\vec{R}-\vec{R}_o|)$, it is very hard to accomplish the integration in (3.2) by any means other than pure numerical integration. If we look at the integral on the rhs of (3.2), we see that this problem is identical to finding the field <u>everywhere</u> in space radiated by a line source locat at (x_o,y_o) and having a current distribution given by $p(z_o)$. In the line source problem, we usually take the point of observation $(\vec{R})$ sufficiently far removed from the source point $(\vec{R}_o)$ that we can invoke far field approximations thereby simplifying (3.2) to the Fourier transform of the "current distribution" $p(z_o)$. In the problems we are dealing with, we <u>cannot</u> invoke such a simplification because we need the field <u>everywhere</u> and particularly near to the source point, for it is the very close points which interact most strongly with the "source." Thus, we see that one of the major difficulties we face is that we cannot invoke <u>conventional</u> asymptotics to simplify the required intergration. In fact, the only meaningful asymptotics we can use in the surface scattering problem are those resulting from limiting forms for the <u>support</u> of $p(z_o)$, i.e., large support resulting from large variance and/or small support resulting from small variance, respectively, for z_o .

the development of a technique which we called the stochastic Fourier transform approach [Brown, 1981; Brown, 1984a]. This research gave us the ability to generalize a number of results which previously had been proven only within the confines of the single scattering approximation [Brown, 1982; Brown, 1983]. Furthermore, the stochastic Fourier transform approach led us to the development of a finite dimensional integral equation of the second kind for the average field scattered by a randomly rough, perfectly conducting surface and also showed how higher moments of the scattered field would be subsequently determined [Brown, 1984a]. While this work clearly showed that there were no fundamental difficulties in formally determining the moments of the scattered field, it did not fully satisfy our second goal which was to provide a computationally tractable solution. To achieve this goal we looked to some of the more classical techniques in random propagation and achieved significant success with the method of smoothing [Brown, 1984a]. The method of smoothing yielded a series expression for the average scattered field in terms of successively higher orders of interactions or multiple scatterings on the surface. Thus, the usefulness of the method of smoothing result hinged largely on the computability of the individual terms in the series and the convergence of the interaction series. Our present efforts have been directed toward answering these questions.

Before discussing our progress on these two issues, it is beneficial to point out a fundamental computational difficulty that one encounters when dealing with the full three dimensional Green's function (for the wave equation) with one random coordinate. To accomplish this, let us consider a very simple random problem, namely that of a randomly positioned point source radiating in free space. Let the particle be positioned at the point (x_o,y_o,z_o) with z_o being random and having a probability density function $p(z_o)$. The scalar field at the point (x,y,z) is given by the three dimensional scalar Green's

3.0 SURFACE MULTIPLE SCATTERING EFFECTS

3.1 Background

The method we have chosen to account for the effects of a layer of foliage upon a rough surface is admittedly approximate. However, it also provides an indication of when our approximations begin to breakdown provided we know, individually, the scattering from the foliage and the rough surface. That is, we must have theories and/or models for scattering from rough surfaces and a slab of foliage which we know are accurate. As noted in Chapter 2, we are still studying the foliage scattering problem to see how far we can go before we are forced to make simplifying approximations to render the problem tractable. However, because of the relatively small volume fraction of a typical foliage covering [Brown and Curry, 1980], we should be able to develop reasonably accurate models for the scattering from a slab of vegetation. The rough surface scattering aspect of the total problem is somewhat more difficult. That is, because of the type of terrain, frequencies, and angles of incidence involved, single scattering theories may not be adequate in general. However, most theories or models for scattering from rough surfaces are limited to single scattering.

Our previous analysis efforts for the rough surface scattering problem have been directed toward two major goals. First, we wanted to determine if the inclusion of multiple scattering presented a fundamental difficulty or one more related to computational complexity. That is, are we limited in our ability to derive basic relationships for the moments of the scattered field or is the inclusion of multiple scattering difficult simply because the computations are hard to accomplish? Our second goal was to develop an approach to the problem which was computationally tractable.

We successfully achieved our first rough surface scattering goal through scattering between particles having differing size, shape, and orientation parameters. We are presently trying to understand the limitations of this approximation.

We are also studying the implications of the dishonest approximation in which the average of the product of two random functions is set equal to the product of the averages of the functions. When we apply this approximation to the coupled integral equations for exponentially weighted current, we obtain a result which does not correspond to the same result we obtain with the first order smoothing approximation. Fortunately, we have been able to understand why this is so. That is, we can show that the dishonent approximation corresponds to shrinking the thickness of the slab to the point where the slab contains only a single layer of particles. Thus, the dishonest approximation accounts for "side ways" multiple scattering between particles but not any "forward" or "back" multiple scattering.

2.4 Future Work

In the previous sections we have attempted to explain our rationale for our particular approach to estimating the effects of a foliage covering on a randomly rough surface. Although our approach is justified primarily by the range of physical and electrical parameters typical for vegetation cover, we find that we cannot completely use the type of weak multiple scattering results that have previously been used to describe the scattering from a vegetation slab in free space. In trying to maintain a degree of rigor in our analysis of the foliage effects, we find the problem to be significantly complicated. Our future efforts will therefore be directed toward simplifying our analysis through the use of approximations whose ramifications are reasonably well understood. Hopefully, we can do this and still maintain a meaningful degree of multiple scattering in our analysis.

positioned particles in terms of the current inside each particle. We multiply this equation by an exponential factor which depends upon the position of the particle in question. The product of this exponential factor and the current forms the integrand of the expression for the scattered field due to each particle. Thus, if we can determine the mean and variance of this product, we can determine the mean and variance of the scattered field due to all particles. By letting the point of observation move inside each particle, we obtain N coupled integral equations for the current in each of the N particles. These integral equations are of the second kind ($\vec{E}_i$ being the source field) and are thus amenable to the method of smoothing. Unlike the surface problem (see Chapter 3), the method of smoothing results in an integral equation for the average of the product of the current and the exponential factor rather than an algebraic result. Our present efforts are being directed toward solving the coupled integral equations without the use of the weak multiple scattering approximation, i.e., no correlation between particles.

In order to solve these coupled integral equations, even in the first order approximation, it will be necessary to introduce some simplifying approximations. Our present efforts are directed toward understanding the ramifications of any approximations we invoke. For example, one of the most difficult of all problems is accounting for the random size, shape, and orientation of the particles comprising the random media. This is a very important element in accounting for multiple scattering between particles. Our investigation of previous efforts which claim to account for multiple scattering in the presence of random particle size, shape, and orientation has shown that the results are very approximate. In particular, the results are only valid when the entire ensemble of particles assumes, in unision, a specific shape, size, or orientation. This is clearly not the same as accounting for multiple of the foliage. The results in Chapter 3 can be used to compute $\langle\vec{E}_{s_s}^{(1)}\rangle$ and $\mathrm{Var}(\vec{E}_{s_s}^{(1)})$ by replacing the "source" term by (2.7) and treating all averages as conditional averages with the foliage random parameters held constant; an additional averaging over the random foliage parameters is then necessary. Because of the assumed independence of the surface and foliage, the final average carries through in a straightforward manner.

We can use weak multiple scatter theory to estimate $\langle\vec{E}_{s_f}^{(1)}\rangle$ and $\mathrm{Var}(\vec{E}_{s_f}^{(1)})$ and such knowledge will also be adequate for computing $\langle\vec{E}_{s_s}^{(1)}\rangle$ and $\mathrm{Var}(\vec{E}_{s_f}^{(1)})$. However, these moments are not, in general, sufficient to compute the variance of $\vec{E}_{s_f}^{(2)}$. This is because, in the backscattering direction, there is a potential for enhancement of the backscattered power due to both the incident and backscattered waves traveling through a highly correlated region of foliage [DeWolf, 1971]. Since weak multiple scatter theory ignores any correlations, it can never predict an enhancement in the backscatter direction. Clearly, we would like to be able to ignore this effect and simply use weak multiple scatter theory to compute $\mathrm{Var}(\vec{E}_{s_f}^{(2)})$; however, there are problems with such an approach. First, the theory developed by DeWolf [1971] applies to continuous random media and, in fact, we have no theory for this effect in discrete random media even though recent measurements have confirmed its existence [Private Communications, A. Ishimaru]. This means that we really have no idea as to the range of media parameters which can give rise to the phenomena. Consequently, we have directed our efforts to describing the scattering from the foliage using methods which include some correlation between particles.

The approach that we are investigating is the method of smoothing; however, we are using it in a manner that has apparently never been done before. First, we set up the equations for the field scattered by all of the randomly this complication, we shall use planar surfaces to bound the foliage layer with the thickness d representing some average thickness. This approximation is reasonable for a sparse concentration of scatterers but it is woefully inadequate for a dense population of scatterers because then the shape of the enclosing volume becomes very important. One other point about our slab approximation is that we should be very suspicious of any results which are sensitive functions of the boundary shape. For example, if in the analysis of the part of the problem given in Figure 1a we find a specularly reflected average field, we know that such a field cannot exist except possibly when the layer thickness is small compared to a wavelength. That is, since the specularly reflected field is a direct consequence of the planar slab boundaries which, in turn, are clearly artificial, we know that a specularly reflected field cannot truly exist.

According to Figure 1, we now have three simplified problems to solve rather than one very complex problem. Because of the interaction or coupling between these problems, we must be able to compute a mean value and a (zero mean) fluctuating part for each field component in (2.3) before we can compute the desired quantities in (2.5) and (2.6). The contribution from the surface is discussed in Chapter 3 and our analysis is based upon the method of smoothing. It must be remembered, however, that the "source" appearing in Chapter 3 as $2\vec{N} \times \vec{H}_i$ should be replaced by

$$2\vec{N} \times [\vec{H}_i + \vec{H}^{(1)}_{s_f}] \qquad (2.7)$$

where $\vec{H}_i$ is the free space incident magnetic field and $\vec{H}^{(1)}_{s_f}$ is the magnetic field scattered by the foliage when illuminated by $\vec{H}_i$. The inclusion of the $\vec{H}^{(1)}_{s_f}$ field accounts for the "first time through" scattering effects

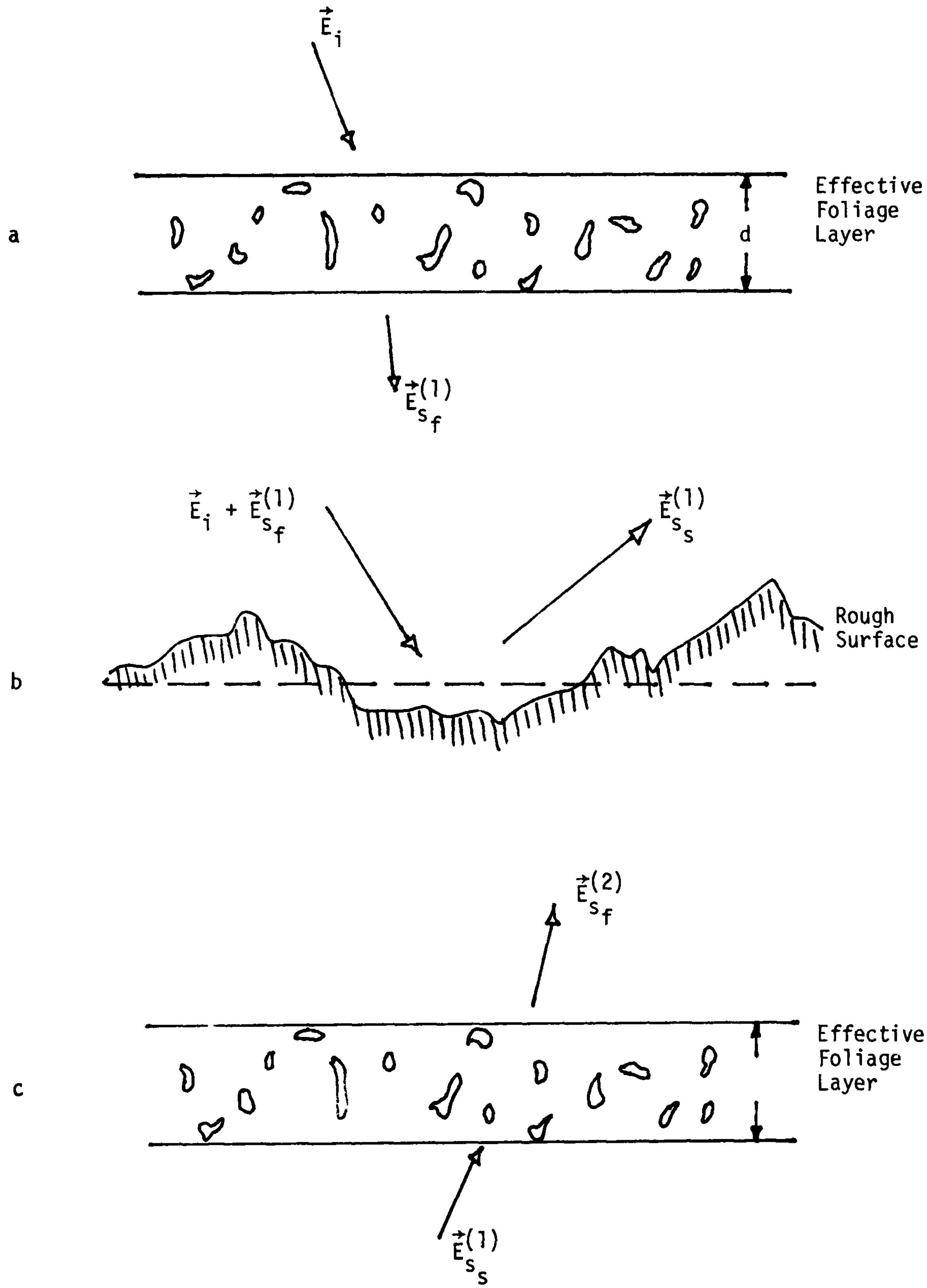

Figure 1. Illustration showing three main contributions to the total scattered field, i.e., $\vec{E}^{(1)}_{s_f} + \vec{E}^{(1)}_{s_s} + \vec{E}^{(2)}_{s_f}$.

$|\vec{E}_i + \vec{E}^{(1)}_{s_f}|$ in the same direction; such a computation would certainly indicate when $\vec{E}_i + \vec{E}^{(1)}_{s_f}$ is no longer the dominant field incident on the rough surface. This observation shows what we feel to be one of the major attributes of this approach, e.g., by a simple comparison of terms we can estimate when the approximations are no longer valid.

2.3 Analysis

The quantities of primary interest to us are the mean and variance of the scattered field which, according to (2.3), are as follows;

$$<\vec{E}_s> = <\vec{E}^{(1)}_{s_f}(\vec{E}_i)> + <\vec{E}^{(2)}_{s_f}(\vec{E}^{(1)}_{s_s})> + <\vec{E}^{(1)}_{s_s}(\vec{E}_i + \vec{E}^{(1)}_{s_f})> \qquad (2.5)$$

$$\mathrm{Var}(\vec{E}_s) = <|\vec{E}_s|^2> - |<\vec{E}_s>|^2 \qquad (2.6)$$

The physical source of each of the field components is shown in Figure 1. $\vec{E}^{(1)}_{s_f}$ is the field transmitted through the foliage when illuminated by $\vec{E}_i$, $\vec{E}^{(1)}_{s_s}$ is the field scattered by the rough surface when illuminated by $\vec{E}_i + \vec{E}^{(1)}_{f_s}$, and $\vec{E}^{(2)}_{s_f}$ is the field transmitted through the foliage slab when illuminated by $\vec{E}^{(1)}_{s_s}$ from below. It should be noted that we have chosen to represent the foliage as enclosed in a slab of thickness d ; this point requires some further discussion. Clearly, for any realization of the foliage, the enclosing boundaries at the top and bottom will not necessarily be planar. This is obvious because the lower boundary of the foliage is, in fact, the rough surface. Thus, from a strictly rigorous point of view, the upper and lower planar slab surfaces should be replaced by randomly rough surfaces. However, this would then require us to take the volume between the two random surfaces to also be random and this would greatly complicate matters. To avoid

(b) the first order field scattered from the surface ($\vec{E}_{s_s}^{(1)}$) is due to both the free space incidence field and the first order field scattered by the foliage, and (c) the second order field scattered from the foliage is due to the first order field scattered by the surface. It should be noted that the presence of the surface forces us to consider a second order field scattered by the foliage in order to properly account for the two-way passage of energy through the foliage. Furthermore, if the foliage becomes a perfectly conducting or absorbing slab, then

$$\vec{E}_{s_f}^{(1)} = -\vec{E}_i \tag{2.4}$$

so that the net field incident upon the surface is zero.

In writing (2.2) we are assuming that it is not necessary to account for <u>more than</u> second order foliage scattering effects or first order surface interactions with the foliage. Physical principles dictate that this approximation should be valid when the dominant mechanism within the foliage is <u>absorption</u> rather than scattering. Fortunately, the results presented by Brown & Curry [1980] indicate that this is the case for the frequencies of interest to this study. We should also note, however, that the approximation in (2.3) will also be valid whenever the foliage constituents are <u>strong forward scatterers</u> for then we would expect the interaction of $\vec{E}_{s_f}^{(2)}$ with the surface (to produce $\vec{E}_{s_s}^{(2)}$) to be very small. In summary, because of the highly absorptive nature of foliage at low frequencies [Brown & Curry, 1980] and the large size of foliage constituents at high frequencies, we expect that (2.2) will be a reasonable approximation over a frequency range that is somewhat larger than one might at first suspect. The accuracy of this statement can be checked by simply comparing the magnitude of $\vec{E}_{s_f}^{(2)}$ in the direction of the surface to

Equation (3.6) is now the appropriate point to apply the asymptotics. Interestingly enough, the $\Delta\zeta$-integration is determined in large by the magnitude of the height variance $\langle\zeta^2\rangle$ while the $\Delta\vec{r}_t$-integration is governed by the normalized correlation function $\rho(\Delta\vec{r}_t)$. <u>For Gaussian distributed heights and slopes</u>, we have found that $\bar{\bar{p}}(\Delta\zeta,\Delta k;\Delta\vec{r}_t)$ is dominated in its $\Delta\zeta$-dependence by a term that is as follows;

$$\frac{1}{\sqrt{2\pi\langle\zeta^2\rangle(1-\rho)}} \exp[-(\Delta\zeta)^2/4\langle\zeta^2\rangle(1-\rho)] \tag{3.7}$$

which readily lends itself to an asymptotic evaluation of the $\Delta\zeta$-integration for both small <u>and</u> large height variance $\langle\zeta^2\rangle$. Clearly, in the limit of small height variance (3.7) behaves like a delta function so (3.6) becomes

$$\lim_{\langle\zeta^2\rangle\to o} \mathrm{LPGf}^i \approx \exp(-j\vec{k}_{i_t}\cdot\vec{r}_{t_1}) \int \phi(0,\Delta\vec{r}_t)\bar{\bar{p}}(0,\Delta k;\Delta\vec{r}_t)\exp(j\vec{k}_{i_t}\cdot\Delta\vec{r}_t)d\Delta\vec{r}_t \tag{3.8}$$

In the case where $\langle\zeta^2\rangle$ is large, we can ignore the exponential term in (3.7) because it is very slowly varying with $\Delta\zeta$ except where $\Delta\vec{r}_t = \Delta\zeta = 0$; however, this point is excluded from the integration because the surface integral in the magnetic field integral equation is of the principal value type. Furthermore, it can be shown that the residual dependence of $\bar{\bar{p}}$ <u>upon</u> <u>$\Delta\zeta$</u> , once (3.7) is removed, is simply

$$\exp[j\Delta\zeta(k+k_{i_z})/2]$$

Thus, in the limit of large height variance (3.6) can be approximated as follows;

$$\lim_{\langle\zeta^2\rangle\to\infty} \mathrm{LPGf}^i = \exp(-j\vec{k}_{i_t}\cdot\vec{r}_{t_1})\int\tilde{\phi}\left(\frac{k+k_{i_z}}{2},\Delta\vec{r}_t\right)\left\{\frac{\bar{\bar{p}}(\Delta\zeta,\Delta k;\Delta\vec{r}_t)}{\exp[j\Delta\zeta(k+k_{i_z})/2-(\Delta\zeta)^2/4\langle\zeta^2\rangle(1-\rho)]}\right\}$$

$$\cdot \exp(j\vec{k}_{i_t}\cdot\Delta\vec{r}_t)\, d\Delta\vec{r}_t \tag{3.9}$$

where

$$\tilde{\Phi}\left(\frac{k+k_{i_z}}{2}, \Delta\vec{r}_t\right) = \int \phi(\Delta\zeta,\Delta\vec{r}_t)\exp[j\Delta\zeta(k+k_{i_z})/2]\, d\Delta\zeta$$

We should point out that the factor in the curly bracket in (3.9) may contain a dependence on $<\zeta>^2$ other than the simple $[2\pi<\zeta^2>(1-\rho)]^{-1/2}$ suggested by (3.7). However, this dependence varies very slowly with $\Delta\vec{r}_t$ so its variation need not be considered in doing the $\Delta\vec{r}_t$-integration.

Equations (3.8) and (3.9) represent the small and large height variance limits for $LPGf^i$. The $\Delta\vec{r}_t$-integrations in (3.8) and (3.9) are governed by the support of the normalized correlation function and its first derivatives or, more explicitly, the correlation length of the surface roughness. Asymptotic evaluation of the integrations for large and small correlation length is not as straightforward as the height variance case. For example, we can consider the limit where the correlation length is much smaller than electromagnetic wavelength only if we let the height variance also be small [Ch. 3, Brown, 1984a]. To date, we have not found a suitable asymptotic method to evaluate (3.8) and (3.9). However, the integrals in these equations can certainly be evaluated by numerical means and this is presently under study.

When we have to consider $N>0$ in the expression $LPG[LG]^N f^i$, there is clearly an increase in complexity because there are $N+2$ random heights and $N+2$ random slopes to be averaged over. However, if we consider only $N=1$, then we feel that it should at least be possible to asymptotically evaluate the height integrations. It is essential that we evaluate the $N=1$ term because we need to know when it is comparable to or exceeds the $N=0$ term; this is a good indication that the retention of only the $N=0$ and $N=1$ terms is inadequate.

3.3 Convergence of the Method of Smoothing

The method of smoothing provides a series solution for the average scattered field[*] in terms of successively higher orders of interaction or multiple scattering on the surface. Instead of performing a term by term average of an iterative solution of the basic integral equation, i.e., the magnetic field integral equation in our case, the method of smoothing iteratively solves for the fluctuating scattered field and uses this result to develop an expression for the average scattered field. The basic logic behind the method of smoothing is that if the fluctuating field is sufficiently small that only a few number of terms in its iterative solution are required then these few terms will be entirely adequate for the average scattered field. While this logic is reasonable, it does not overcome the need for a rigorous proof for convergence of the resulting series. To our knowledge, no one has ever demonstrated the convergence of the method of smoothing and our work is no exception. We have devoted a great deal of time to trying to establish the conditions under which the method of smoothing converges but to no avail. The primary difficulty is the nearly impossible task of estimating the relative magnitude of successively higher order terms. While this is certainly an interesting and challenging research task, we do not feel that it is suitable to an applications oriented project such as this. Consequently, we do not anticipate spending any further time and effort on the general convergence issue.

Fortunately, we have been able to demonstrate the advantages of the method of smoothing relative to the standard iterative approach to solving the magnetic field integral equation. This topic is discussed in detail in [Brown, 1984b] and so we will only briefly review the major highlights. For an integral

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[*] It should be noted that this result can also be used to find the incoherent scattered power [Ch. 4, Brown, 1984a].

equation of the second kind, such as the magnetic *field integral* equation, having the following form;

$$f = f^i + LGf \tag{3.10}$$

the standard iterative solution is given by

$$f = \sum_{n=o}^{\infty} [LG]^n f^i \tag{3.11}$$

The average of this result yields

$$\langle f \rangle = P \sum_{n=o}^{\infty} [LG]^n f^i \tag{3.12}$$

where P denotes the averaging operator, i.e., $P = \langle \cdot \rangle$. The problem with (3.12) is that it involves an infinite number of interactions between both average terms <u>and</u> zero mean fluctuating terms. That is, even if the fluctuating part of f is very small, (3.12) still comprises an infinite series of interacting average terms. The method of smoothing overcomes this problem by <u>summing</u> all of the interactions between average terms; that is, if the fluctuating part of f is vanishingly small, the method of smoothing yields an <u>exact</u>, <u>closed</u> <u>form</u> result for $\langle f \rangle$. The method of smoothing does this in the following very clever manner. It recognizes that in iteratively solving for f as in (3.11), one is iterating on <u>both</u> the average value of f <u>and</u> its zero mean fluctuating part and this causes problems even when the fluctuating part of f is small because one is left with an infinite series even when the fluctuating part of f is very small. To overcome this, the method of smoothing iteratively solves for the fluctuating part of f <u>only</u>. This result is self consistently used to solve for $\langle f \rangle$ in a non-iterative fashion. Now, since the only infinite series in the solution for $\langle f \rangle$ results from the iterative series for the fluctuating part of f, one obtains a <u>closed form</u> solution for $\langle f \rangle$ when the fluctuating part of f (and its series solution) shrinks to zero. This is the real advantage of the method of smoothing relative to a standard iterative solution. Unfortunately, it is not always obvious when the fluctuating part of f is sufficiently small and this is why it is difficult, in general, to establish the range of parameter variation for which the resulting series converges.

3.4 <u>Future Work</u>

Since the major thrust of our research is to be directed toward the foliage effects problem, our surface scattering research will necessarily be reduced. However, we do plan to continue on with the asymptotic evaluation of the terms in the method of smoothing series. In particular, we hope to be able to accomplish all of the random variable integrations and, thus, to reduce the required integrations to ones over the differences in the transverse spatial coordinates such as $\Delta\vec{r}_t$ in (3.8) and (3.9). We then plan to continue investigating appropriate approximations for the normalized surface height correlation function which enable us to asymptotically evaluate these integrals (without simply yielding more or less trivial results). If we are successful in this research, we feel that we should be able to make some definitive statements in regard to the convergence of the method of smoothing series at least in these asymptotic limits.

As we have noted previously in this report, we feel that the method of smoothing series has a much greater potential for providing an immediate answer to the random surface scattering problem. Consequently, we do not plan to pursue the stochastic Fourier transform approach during this present effort. We feel that further study of this approach is best left to future dedicated efforts.

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